CAL Memo CAL/NUSTAR/2012-001

NuSTAR FPM Calibration Data in the HEASARC Calibration Database

Michael F. Corcoran
Code 662,
NASA/GSFC,
Greenbelt,
MD 20771

Version: 2012-Feb-22

SUMMARY

This document describes the structure of the NuSTAR calibration database (CALDB) at the HEASARC. It includes brief descriptions of the data files, update plans, and retrieval information.

LOG OF SIGNIFICANT CHANGES

Release	Sections Changed	Brief Notes
2012 Feb 22	All	First Draft
2013 Aug 15	All	updated for 20130509 NuSTAR CALDB
2013 Aug 20	All	comments by KF and BG
2013 Nov 20	All	updated for changes in 20131007 caldb release

Contents

List of Tables

1 Introduction

1.1 NuSTAR

NuSTAR, The Nuclear Spectroscopic Telescope Array Mission, is the first focusing high-energy X-ray mission, opening the hard X-ray sky for sensitive study for the first time. NuSTAR will search for black holes, map supernova explosions, and study the most extreme active galaxies.

The NuSTAR mission deployed in space the first focusing telescopes to image the sky in the high energy X-ray (5 – 80 keV) region of the electromagnetic spectrum. NuSTAR's low background and spatial resolution offers particular advantage over previous coded aperture experiments that have traditionally been used to image the sky at energies above 10 keV.

During a two-year primary mission phase, NuSTAR will map selected regions of the sky in order to:

- take a census of collapsed stars and black holes of different sizes by surveying regions surrounding the center of own Milky Way Galaxy and performing deep observations of the extragalactic sky;
- map recently-synthesized material in young supernova remnants to understand how stars explode and how elements are created; and
- understand what powers relativistic jets of particles from the most extreme active galaxies hosting supermassive black holes.

NuSTAR was launched at 9 am PDT, June 13, 2012 on a Pegasus XL rocket which was dropped from a Lockheed 10-11 aircraft flying over the Pacific Ocean near Kwajalein Island. NuSTAR is in a low-earth (altitude ~ 620 km) low-inclination ($i \sim 6°$) orbit. The NuSTAR Principal Investigator is Prof. Fiona Harrison of Caltech. The Project Scientist is Dr. Daniel Stern (JPL/Caltech) and Suzanne Dodd (JPL/Caltech) is the NuSTAR Project Manager. Orbital designed, manufactured, integrated and tested the NuSTAR satellite, under contract from the California Institute of Technology and the Jet Propulsion Laboratory.

1.1.1 Mirrors

The NuSTAR instrument consists of two co-aligned grazing incidence telescopes with specially coated optics and newly developed detectors that extend sensitivity to higher energies compared to previous missions such as *CHANDRA* and *XMM*. NuSTAR uses a conical approximation to the usual Wolter-I mirror design. Each NuSTAR mirror consists of 133 concentric conical multi-layer mirror shells. The NuSTAR mirror substrates are thin sheets of flexible glass, akin to laptop and cellular phone displays, which are heated in an oven and slumped over precision polished cylindrical quartz mandrels to achieve the right curvature. To extend the efficiency of X-ray scattering at energies above 10 keV, the NuSTAR mirrors are coated with "depth-graded multilayers". These multilayers are thin coatings of two alternating materials deposited one on top of the other. A typical multilayer has 200 pairs of coatings. Enhanced reflectivity requires a high density contrast between the two coatings. Common high density materials are tungsten (W) and platinum (Pt), while common materials for the low density layers are silicon (Si), carbon (C), and siliconcarbite (SiC). The multilayer stack acts as a crystal lattice and constructive interference creates enhanced reflectivity at high energies, superior to a single mirror reflection. NuSTAR uses platinum/siliconcarbite (Pt/SiC) and tungsten/silicon (W/Si) multilayers, allowing the mirrors to reflect photons at energies up to 79 keV. Above this energy, platinum starts absorbing rather than reflecting X-rays. The mirror segments were formed at the Goddard Space Flight Center in Greenbelt, MD, coated at the Danish Technical University in Copenhagen and finally assembled at Columbia University's Nevis Laboratory in New York.

1.1.2 Extendable Mast

The NuSTAR mirrors have an overall length of 450 mm, a maximum radius of 191 mm and a focal length of 10-meter. The NuSTAR telescope is equipped with an extendable mast in order to fit within the payload fairing of the Pegasus launch vehicle. In its stowed configuration during launch, the mast fits in a space less than two meters in length. After deployment, the mast was extended to its full 10-meter focal length. An alignment mechanism on the NuSTAR mast was used at the beginning of the mission to align the telescope. Additionally, because the mast undergoes thermal flexing when going in and out of Earth's shadow, NuSTAR also includes a metrology system consisting of two lasers on the optics end that are pointed at three light-sensing detectors at the detector end of the telescope. Measurements from the laser metrology system are used to correct the X-ray images for blurring due to the mast motion.

1.1.3 Detector System

NuSTAR has two detector units, Focal Plane Module A (FPMA) and Focal Plane Module B (FPMB), each at the focus of one of the two co-aligned NuSTAR mirrors, which observe the same area of sky during a NuSTAR pointing. The focal planes are each comprised of four 32×32 pixel cadmium-zinc-tellurium (CdZnTe, or CZT) detectors manufactured by EI Detection & Imaging Systems (formerly eV Microelectronics) of Saxonburg PA. CZT detectors are state-of-the-art room temperature semiconductors that are very efficient at turning high energy photons into electrons. The electrons are then digitally recorded using custom Application Specific Integrated Circuits (ASICs) designed by the NuSTAR Caltech Focal Plane Team.

1.2 Science Data Processing Overview

Science data is processed at the NuSTAR Science Operation Center (SOC) in Caltech automatically upon transmission from ground stations, typically about four times every day. Once the science quality of completed observations has been validated by the SOC, the observations are then transferred electronically to NASA's High Energy Astrophysics Science Archive Research Center (HEASARC) at the Goddard Space Flight Center in Greenbelt, MD. The HEASARC serves as the science archive for NuSTAR data. All data from the NuSTAR satellite will be made publicly available from the HEASARC.

The SOC also has responsibility for generating the calibration data and making those data available for transfer to the HEASARC for archiving in the HEASARC's Calibration Database.

1.3 The HEASARC Calibration Database

The HEASARC's calibration database (CALDB) system stores and indexes datasets associated with the calibration of high energy astronomical instrumentation. The system can be accessed by users and software to determine which calibration datasets are available, and which are appropriate for data reduction and analysis. Data in the CALDB which is to be used in analysis must be stored in FITS format, and must include specific FITS header keywords as described in "Required and Recommended FITS keywords for Calibration Files" (CAL/GEN/92-011)The HEASARC also distributes a set of access routines, called the `caltools`, as part of the HEASoft multi-mission analysis system. The HEASARC CALDB access software is supported on every operating system that is supported by the HEASoft software suite. This includes almost all flavors of Unix (including linux and Mac OS X). There is currently no support for versions of the Microsoft Windows operating system.

The CALDB for any and all supported missions can be downloaded and installed on a user's machine for any analysis task. Alternatively, users can remotely access the HEASARC CALDB without having to download, install or maintain a local copy of the CALDB (which can be rather large, and which can be updated rather frequently). Analysis software included in the HEASoft package includes CALDB access support. This simplifies the identification and use of calibration data appropriate to the observation being analyzed. *However*, processing time will depend on data transfer rates and may be long for users with slow internet connections. This seems to be especially the case when running the NuSTAR processing routine `nupipeline` using remote access to the NuSTAR CALDB since some large files get repeatedly transferred over the network which can cause excessive delays.

2 Structure of the NuSTAR CALDB

Calibration data in the CALDB are stored in sub-directories of some top-level directory defined in the Unix environment variable `$CALDB`. For the HEASARC CALDB, the environment variable `$CALDB` may be defined as `http://heasarc.gsfc.nasa.gov/FTP/caldb`, which is often useful for users to remotely access CALDB data via the internet without having to install a version of the CALDB on a local disk. Remote access to the CALDB is described on the "CALDB Remote Access" document at `http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/caldb_remote_access.html`. Users may copy the NuSTAR CALDB to their own machines for easier access by downloading a single tar file, in which case a local `$CALDB` environment variable needs to be defined, as described in "How to Install a Calibration Database" (cal/gen/94-004).

Subdirectories of the `$CALDB` directory include `data`, `docs` and `software` subdirectories.

2.1 The `docs` subdirectory

The `docs` subdirectory contains documentation describing the calibration data for given missions. NuSTAR-specific calibration documentation describing types of calibration data, uncertainties in the calibrations, applications of the calibrations, and other descriptive matter (including this document) will be located in the `docs/nustar` subdirectory. Documents describing the structure and use of the CALDB as instituted at the HEASARC will be stored in the `docs/memos` subdirectory.

2.2 The `software` subdirectory

The `software` subdirectory contains various scripts and procedures used for CALDB maintenance. The `software/tools/` subdirectory contains setup and initialization files used by the CALDB, in particular:

- `caldbinit.csh`, `caldbinit.sh`, `caldbinit.vms` and `caldbinit.iraf`: these files define necessary CALDB environment variables for c-shell, bash shell, VMS (no longer supported) and IRAF users, respectively.
- `caldb.config`: this is an ASCII text file which provides necessary information regarding the configuration of individual mission CALDBs.
- `alias_config.fits`: this FITS file provides the list of "aliases" for the names of particular instruments on particular missions.

2.3 The `data` subdirectory

The NuSTAR CALDB follows the general CALDB structure in which calibration data are divided, for largely historical reasons, into two types, "basic calibration files" (bcf), consisting of FITS-formatted calibration data primitives, and "calibration product files" (cpf), FITS-formatted calibration data which are (usually) derived from the "basic calibration" primitives. A discussion of the differences between "bcf" and "cpf" data is given in CAL/GEN/92-003, "BCF & CPF Calibration File Guidelines". For a given mission and instrument, the calibration data are stored in CALDB subdirectories whose directory path is specified by the mission and instrument name, according to the "type" of data (basic calibration or calibration product). Data for the NuSTAR Focal Plane instruments will be stored in `$CALDB/data/nustar/fpm/<type>`, where `<type>` is either `bcf` or `cpf`, depending, respectively, on whether the file is assigned to the basic calibration file or calibration product file type, and `$CALDB` is a variable pointing to the user's top-level CALDB. Figure 1 shows a brief overview of the NuSTAR CALDB directory organization, while Table 1 and 2 gives a brief overview of the FPM CALDB `cpf` and `bcf` subdirectories.

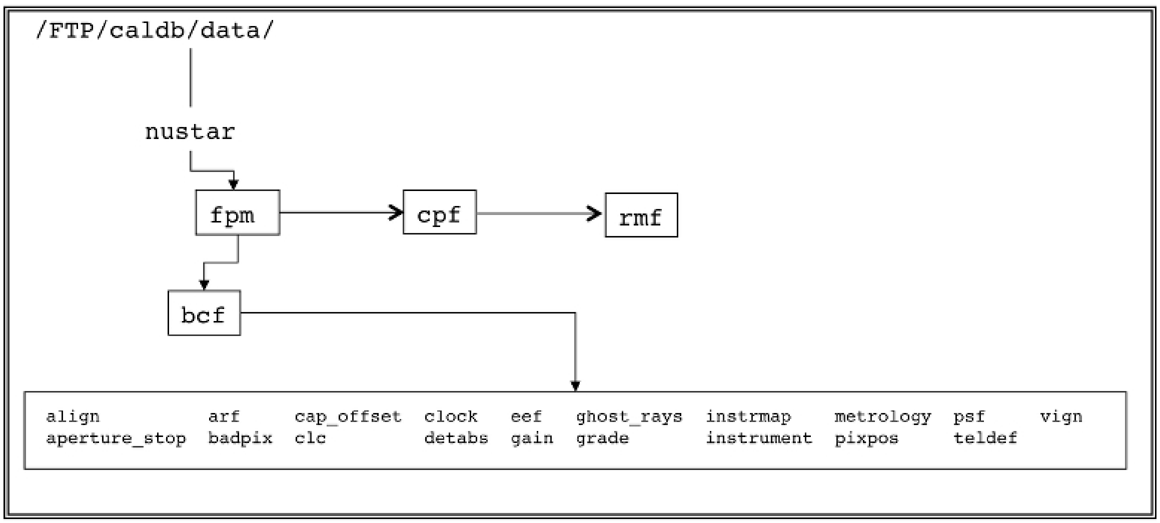

Figure 1: Map of the NuSTAR CALDB data directory (as of the 20131007 release).

3 NuSTAR CALDB Codenames Values: the CCNM0001 keyword list

Calibration data in the calibration database can be identified by codenames given by the CALDB keyword `CCNM0001` in the header of the calibration file extension. Table 3 lists the values of the CCNM0001 keywords, with brief descriptions, in use by the NuSTAR mission to describe NuSTAR CALDB data. For all tabulated entries, the keywords `TELESCOP='NUSTAR'` and `FILTER='INDEF'`.

Table 1: Brief Descriptions of the NuSTAR CALDB Basic Calibrations File Directory Structure for the FPM. These subdirectories are located in `$CALDB/data/nustar/fpm/bcf/`. Directory structure based on the 20130509 NuSTAR CALDB release.

Subdirectory	Description
align	focal plane alignment and quarternions
aperture_stop	aperture stop ARF correction
arf	Effective areas (ancillary response file format) for FPMA and FPMB
badpix	Bad pixel positions for each CZT detector
cap_offset	For each pixel of the hybrid, the 16 OFFSET values corresponding to the 16 capacitors for each pixel.
clc	charge loss correction coefficients for events with charge split between multiple pixels.
clock	NuSTAR clock correction files
detabs	additional absorption along the optical path, incorporated in the ARF during processing.
eef	encircled energy functions for the imaging detectors
gain	gain information for each detector pixel
ghost_rays	ghost rays ARF correction
grade	grade classification definitions for detected events
instrmap	information for producing exposure maps (DET1 instrument probability maps).
instrument	General instrument parameters (housekeeping ranges, acceptable event ranges, etc)
metrology	calibration of the position sensitive diode detectors of the metrology system used in mast motion reconstruction.
pixpos	statistics on probability that a particular event was located at a detected pixel
psf	raytrace 2D PSF files
teldef	general telescope definition parameters
vign	Optics vignetting information

Table 2: Brief Descriptions of the NuSTAR CALDB Calibration Product File Directory Structure for the FPM. These subdirectories are located in `$CALDB/data/nustar/fpm/cpf/`. Directory structure based on the 20130509 NuSTAR CALDB release.

Subdirectory	Description
rmf	NuSTAR response matrices

Table 3: Summary of NuSTAR CALDB File Codes (CAL_CNAM). Based on the 20130509 NuSTAR CALDB

CAL_CNAM	Description
2D_PSF	2-dimensional point spread function image
ALIGNMENT	NuSTAR Optical Axis position
BADPIX	NuSTAR Ground Bad Pixel Table
CAP_OFFSET	NuSTAR capacitor offset values
CHUOFFSET	NuSTAR detector to camera head unit 4 offset quarternion
CLC	NuSTAR charge loss coefficients
DEPTHCUT	NuSTAR depth cut coefficients
DETABS	NuSTAR detector absorption coefiicients
EBOUNDS	NuSTAR energy boundaries
EVTCUT	NuSTAR event cuts coefficients
EVTRANGE	NuSTAR GRADE and STATUS range values
GAIN	NuSTAR Gain coefficients
GHOSTRAYS	NuSTAR ghost rays arf correction
GRPRMF	NuSTAR response matrix file grouping
GRADES	NuSTAR Grade
HKRANGE	NuSTAR Housekeeping range values
INSTRMAP	NuSTAR instrument map
MATRIX	NuSTAR Response Matrix
METROLOGY	NuSTAR Metrology Calibration Data
MKFCONF	NuSTAR makefilter parameters
PHAPAR	NuSTAR Energy Calibration Coefficients
PIXPOS	NuSTAR Pixel Position Coefficients
PRECONF	NuSTAR pre-filter parameters
REEF	Raytrace-LVDT Encircled Energy Function
SAAPAR	NuSTAR SAA parameters
SPECRESP	NuSTAR FPMA Ancillary Response File
TELDEF	TELESCOPE DEFINITION FILE
TVIGNET	NuSTAR FPM Vignetting

4 CALDB Updates

Updates to the CALDB are described by the procedure in "Automated Delivery of Calibration Data to the CALDB" (cal/gen/2003-001). Ingest data scripts are located in `$CALDB/local/scripts/DATA_DELIVERIES` at the HEASARC. Data to be ingested can be placed in appropriate subdirectories in `$CALDB/staging/data/nustar`. Each update to the NuSTAR CALDB will be listed on the CALDB "What's New" webpage, and also announced via the CALDB RSS NewsFeed.

Updates to the NuSTAR clock calibration FITS file will be made available between CALDB releases at the NuSTAR SOC website at Caltech:

`http://www.srl.caltech.edu/NuSTAR_Public/NuSTAROperationSite/Home.php`

Updates to the clock calibration file are expected to be available on a monthly timescale.

5 General Calibration Data

The NuSTAR mission may use general calibration data which may be used by many various missions.

Table 4: General Calibration Files Available for Use by NuSTAR

Type of File	CCNM0001 Value	CAL_DIR	CAL_DESC	Sample
Leap Seconds Table	LEAPSECS	$CALDB/data/gen/bcf	Table of times at which Leap seconds occurred	leapsec_010905.fits

6 CALDB Data Access

NuSTAR data in the CALDB can be retrieved by a number of mechanisms. Users can directly access files via anonymous ftp from `ftp://legacy.gsfc.nasa.gov/caldb/data/nustar`, or via the WWW from `http://heasarc.gsfc.nasa.gov/FTP/caldb/data/nustar`, if the user knows the name and location of the file. This is not very convenient when a user needs to choose from a number of versions of the same file, since it may not be clear which version is applicable to the analysis task at hand. The tool `quzcif`, distributed as part of the HEASoft `caltools` package, allows users to determine which calibration file (or files) are appropriate for a given analysis task after the user specifies a given set of observing parameters (date and time of observation, instrument, and other relevant parameters). After the relevant observing parameters are specified, `quzcif` returns the names of the appropriate files from the CALDB. The HEASoft calibration software library (`callib`) FORTRAN subroutine `gtcalf` can be used by individual software tasks to retrieve relevant calibration data from the CALDB with little or no user input. A description of `gtcalf` is given in "HEASARC CALDB Access Subroutines" (cal/sw/95-002).

This subroutine may evolve as new capabilities are required; users should check the latest distribution of the HEASoft package for the latest version of the `gtcalf.f` subroutine.

Users of the HEASoft software (or any software that supports virtual file input using `urls`[1] (like software based on the CFITSIO library) and an internet connection can also access the HEASARC CALDB remotely (i.e. without having to install the CALDB locally).

The CALDB website has more information on installing and managing the CALDB, and information on accessing the CALDB remotely.

7 CALDB Websites

The CALDB homepage is `http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/`. General information regarding the NuSTAR CALDB, including links to tarfiles of NuSTAR calibration data and dates of updates, will be made available on the CALDB supported missions webpage and announced on the CALDB rss feed, and included on the CALDB "What's New" web page. For each NuSTAR CALDB release, a summary of the current calibration files will be available from the NuSTAR CALDB summary page.

[1] Uniform Resource Locator

8 Relevant NuSTAR Resources

- "The Nuclear Spectroscopic Telescope Array (NuSTAR) High Energy X-ray Mission", Harrison et al., (2013) ApJ 770, 103
- Interface Control Document NuSTAR – HEASARC, Angelini, 2011 (JPL D-48872)
- Memorandum of Understanding NuSTAR – HEASARC, Angelini, 2009
- The NuSTAR Science Operations Center website at Caltech
`http://www.srl.caltech.edu/NuSTAR_Public/NuSTAROperationSite/Home.php`
- The NuSTAR Website at Caltech, `http://nustar.caltech.edu`

9 Relevant HEASARC Documents

- "The HEASARC Calibration Database (a brief overview)" (cal/gen/91-001)
- "The Organization of the HEASARC CALDB" (cal/gen/93-006)
- "Automated Delivery of Calibration Data to the CALDB" (cal/gen/2003-001)

10 Other Useful Webpages

- Other OFWG FITS Format Documentation:
`http://heasarc.gsfc.nasa.gov/docs/heasarc/ofwg/ofwg_recomm.html`
- The CALDB Documentation Library:
`http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/caldb_doc.html`
(contains descriptions of other FITS data file conventions and standards)
- The HEASARC FITS Resource Page:
`http://heasarc.gsfc.nasa.gov/docs/heasarc/fits.html`